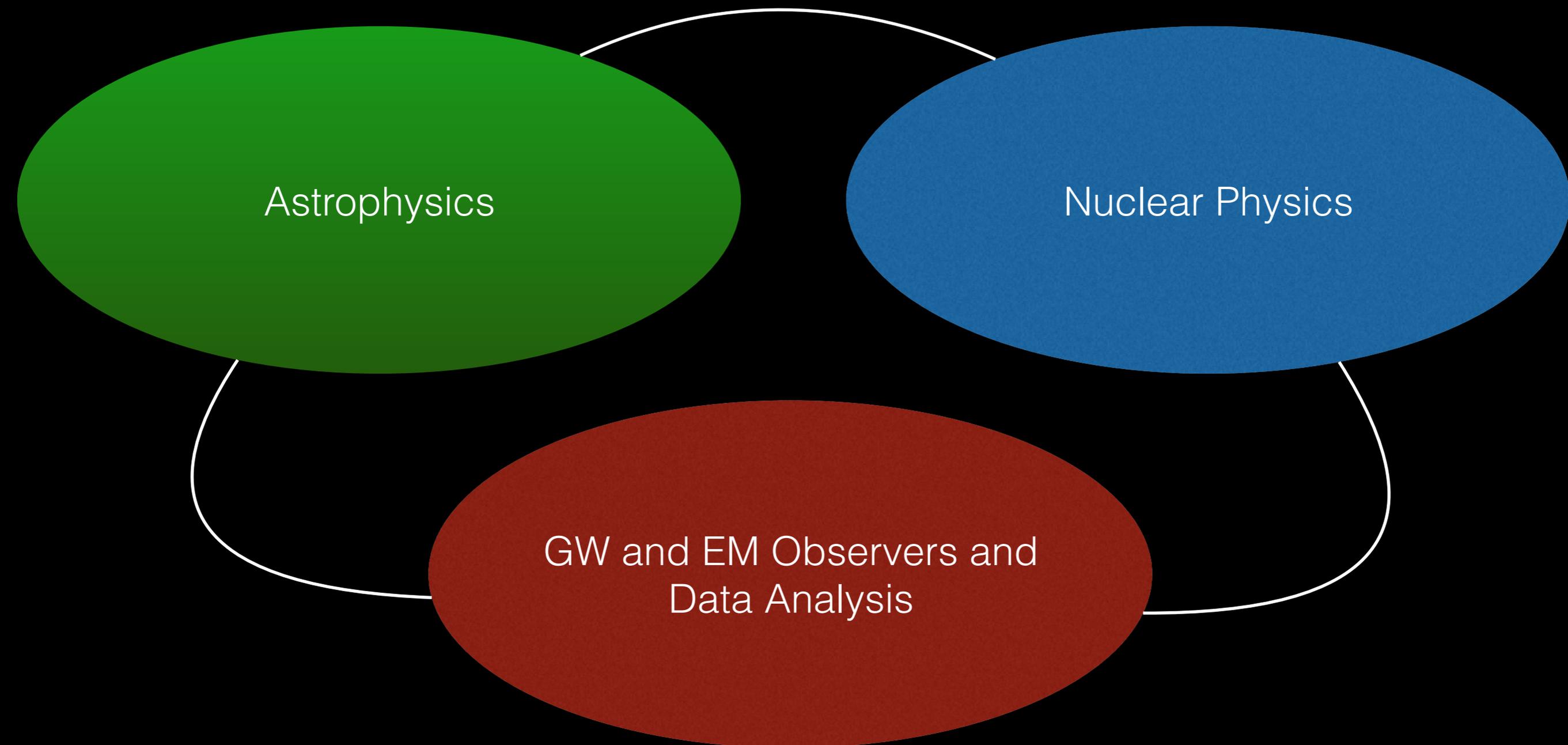# Nuclear Astrophysics in the Gravitational Wave Astronomy Era

12 - 16 June 2017, ECT* (Trento, Italy)

Workshop Summary

Astrophysics

Nuclear Physics

GW and EM Observers and
Data Analysis

These are exciting times !

- Gravitational waves are detectable.
- Necessary conditions for the r-process are realized in NS-NS and NS-BH mergers.
- Limits on NS merger rates from Ad. LIGO will help address the long standing question "Where are the heavy elements made ?"
- Developments in numerical relativity and astrophysics have shown that NS-NS and NS-BH mergers can modeled.
- Data analysis tools for NS parameter estimation are developing rapidly - aided by numerical relativity.
- Some material is ejected. We have begun to understand correlations between mass ejecta, composition, and gravitational waves.
- Electromagnetic counterparts offer a rich phenomenology. SGRBs, Kilonova/Macronova, and radio afterglows probe the central engine.
- A theoretical framework to quantitatively describe the EOS and response of matter up to 5×10^{14} exists.
- There is coordination to develop high-fidelity models of mergers and supernovae with realistic inout physics.
- The role of neutrinos and magnetic fields is being explored in detail.

There are uncertainties and challenges

- Are the NS mergers rates large enough to be useful ?
- Can we tame systematic errors associated with parameter estimation to measure the neutron star radius to <10%?
- Are GW signatures of post merger dynamics robust ? How do turbulent viscosity and transport properties influence the outcomes ?
- Are Kilonova/Macronova observable with current instruments ?
- Can galactic chemical evolution and observed nucleosynthetic abundances usefully constrain merger rates and ejecta mass ?
- Can we describe matter at $\rho > 5 \times 10^{14}$ g/cm^3 and T > 20 MeV ? And are these details essential to interpret signals from post merger dynamics ?
- Will nuclear models be able to describe fission dynamics and beta-decay rates to disentangle the astrophysics ?
- Do we have access to the computational resources to properly model neutrino transport and magnetic field evolution including turbulence and viscosity ?

Take home messages for the nuclear physicists:

- NICER x-ray waveform data from at least one NS, possibly more, will likely measure the NS radii at the 5% level. [Miller]
- Extracting neutron star radii from GW observations will be a horrendous task but could be done over the next five to ten years. [Sathyaprakash]
- GW observations for constraining the EOS rely on detailed waveform models from analytical/numerical relativity. [Bernuzzi]
- Dynamical ejecta from NS mergers makes the strong r-process. There is qualitative agreement between groups, but we are years away from making quantitative predictions (factor of 2). [Radice]
- We need to better understand the impact of nuclear physics inputs on the r-process heating rate. [Fernandez]
- More models of solid phases in the QCD phase diagram. [Horowitz and Jones]
- Role of three-body forces needs to be clarified and NN potential based on quark degrees of freedom need to be studied. [Burgio]
- The universal (EOS independent) relations for the frequency and damping time are robust. [Chirenti]
- Future x-ray missions such as IXPE and XIPE can constrain the EOS (burst oscillations) and probe NS dynamics. [Stella]

Take home messages for the Astrophysicists:

- X-ray information (in 1-2 years) and gravitational wave information (in 5-10 years) on neutron stars will be independent enough to provide complementary tests. [Miller]
- The composition of the dynamical ejecta needs to be understood better. Uncomfortably large differences between groups need to be addressed. Magneto-turbolence needs to be investigated. [Radice]
- Understanding the (general relativistic) strong-field dynamics is crucial for connecting to and identifying the astrophysical emissions. [Bernuzzi]
- Continue an open dialog on code comparisons to help disentangle differences in the output between groups. [Endeve]
- Better understand the relation between GRBs & Kilonovae. [Fernandez]
- Use inputs coming from microscopic theories in your simulation codes, especially when those inputs are well tested.[Burgio]
- Eccentric NS-NS mergers can tidally excite f-modes in cold, non-rotating neutron stars, and provide simultaneous mass, moment of inertia and tidal Love numbers. [Chirenti]
- Need to think about mechanisms for building mountains (as opposed to just working out maximum sizes). [Jones]
- Weak interactions need to be implemented in the modeling of binary compact merger, they are essential to describe dynamics and set the properties of the ejecta. [Perego]

Take home messages for EM & GW observers

- Please be aware that a good statistical fit need not imply an unbiased result ! [Miller]
- We need phase-coherent models for inspiral and post-merger regimes to break degeneracies present in the inspiral phase of the signal. [Sathya]
- Continue to monitor accreting and magnetized neutron stars to study thermal evolution and dynamics. [Cumming]
- We have obtained significant results in recent years on the modeling GW from BNS that will allow us extract useful information as soon as data comes in; we keep on working to include more effects (spins, EOS, etc.) and increasing the accuracy of our models. [Bernuzzi]
- Our current qualitative understanding of the kilonova/macronova emission is robust, but quantitative questions need to be addressed.[Radice]
- Keep searching for kilonova signatures in SGRBs & for precursors. [Fernandez]
- Microphysics and neutrino-matter interactions can have a direct impact on the merger observables. [Perego]
- Need to improve the sensitivity of the gravitational wave detectors at high frequencies (1.5-2 kHz) to learn about structure and equation of state of neutron stars from oscillation modes. [Chirenti]
- More observations targeted at seeing stellar oscillations in NSs (LMXBs say) would be great. [Jones]

Buddha - I want to have your peace, wisdom and serenity.
Who am I kidding, just give me a NS-NS merger or a galactic supernova and I'll let you be.